A (RE)INTERPRETATION OF THE QCD PHASE TRANSITION AND OF STRANGENESS AS QGP SIGNATURE

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The temperature at the chemical freeze-out and at zero baryochemical potential has been extracted in a global analysis of e^+e^-, $p+p$, $p+\overline{p}$ and $A+A$ collisions at $\sqrt{s}$=2-1800 GeV per N+N pair. We demonstrate that the temperature at μ_B=0, rises with the initial energy density ϵ_i, and saturates above $\epsilon_i \sim 1$ GeV/fm^3. This behaviour is interpreted as mapping out the QCD phase transition universally in particle and nuclear collisions. The critical energy density is therefore identified to be $\epsilon_{crit} \sim 1 \pm 0.3$ GeV/fm^3. We show that strange particles at μ_B=0, are not significantly enhanced in A+A collisions as compared to $p+\overline{p}$. The so called 'strangeness suppression factor' ($\lambda_s = \frac{(2\overline{s})}{(\overline{u}+\overline{d})}$) as a function of ϵ_i is following the temperature, rising and saturating universally above ϵ_{crit}. This leads to a reinterpretation of strangeness enhancement as QGP signature. Within this interpretation the experimental puzzles with respect to strangeness production can be naturally explained: e.g. the recent measured maximum of K^+/π^+ in Pb+Pb collisions at 40 A GeV, is explained as due to μ_B. We discuss under which conditions 'strangeness enhancement' and 'J/Ψ suppresion' both set in at $\epsilon_{crit} \sim 1$ GeV/fm^3.

1 Introduction

One outstanding prediction of the theory of strong interaction (e.g. [1,2]) is the phase transition from confined hadrons to a deconfined phase of their constituents, the quarks and gluons (the so called quark gluon plasma =QGP). An experimental program which started approximately in the eighties and continues in many accelerators as: CERN SPS, BNL RHIC, CERN LHC and GSI SIS, has been dedicated to the experimental verification of this transition.
There is at present evidence that the QCD phase transition occurs in central Pb+Pb reactions at 158 A GeV [3]. The major evidence [3] is 1) the suppression of the $J/\Psi/DY$ ratio [4], 2) the enhancement of strange particles and in particular of strange antibaryons [5] and 3) enhancement of γ, $\mu^+\mu^-$ and e^+e^- production [6,7,8,9]. New results from RHIC added a fourth item,

namely indications of jet quenching [10]. However, many aspects of the experimental data remain theoretically unclear and are even selfcontradicting:
(1) An example of unclear interpretation concerns the pattern of $J/\Psi/DY$ suppression. For example it can be described by one [12] or two suppression steps [11], or within approaches without QGP formation [13].
(2) An example of selfcontradiction is strange particle production. Strange particle enhancement is considered by several authors as QGP signature, at and above SPS energy [14]. However this enhancement (when defined as double ratio of: K/π(A+A/p+p)), increases with decreasing $\sqrt{s}$ [15]. This behaviour is the opposite as expected, as the transition should occur in the highest ϵ_i and not in the lowest. Other authors [16] conclude from the latter observation, that it seems –phenomenologically– better to compare the $\sqrt{s}$ dependence of K/π in A+A reactions only, without comparing to p+p. They also propose that the K/π ratio would signal the transition, through a sudden drop towards the higher $\sqrt{s}$, at the critical $\sqrt{s}$. Therefore the QGP signature would be 'strangeness suppression' –towards the higher $\sqrt{s}$ – and not 'enhancement'. Such a drop has indeed been observed in Pb+Pb collisions between 40 and 158 A GeV [17]. Some authors (e.g. [18]) conclude that the data on strange particle production agree but do not prove QGP formation. Another puzzling observation is that strange particles are enhanced also in p+A collisions as compared to p+p [19a] –puzzling because of the implied assumption that the QCD phase transition does not occur in p+p, p+A and peripheral A+A reactions.
Indeed, mostly, all signatures of the QGP are extracted comparing central A+A reactions mainly to p+p, p+A and peripheral A+A collisions and to models which have been shown to reproduce the latter reactions without invoking QGP formation. This comparison implies the assumption that no QGP can be formed in the latter reactions. This assumption is however a priori unproven.

In this paper we address the following questions:
a) Is there a simultaneous appearance of all QGP signatures ? We will mainly address the two QGP signatures of '$c\overline{c}$ suppression' and 's and $\overline{s}$ enhancement' [20], because of lack of measurements of the other signatures at low ϵ_i.
b) Is there evidence for the QCD phase transition in global observables showing a discontinuity, beyond rare probes as the J/Ψ or the Ω data ? [21,2].
c) Can we extract the critical energy density (ϵ_{crit}) above which the QCD phase transition occurs? [2].
d) Is the initial energy density (ϵ_i) the only discriminating parameter for this transition, or is there in addition a 'critical' volume which must be reached –to achieve equilibrium– ? In other words, can the QGP phase transition occur in reactions of leptons and/or hadrons or only in nuclear reactions ? [21,2].
e) Can we explain the above mentioned puzzles (2) which concern the production of strange particles ? Is strangeness a QGP signature ? If so, is strangeness enhancement or suppression a QGP signature ? [22].
We follow these questions one by one in the subsequent sections.

2 Is there a simultaneous appearance of all QGP signatures ? – Question (a)

The increase of $m(e^+e^-)$, $m(\mu^+\mu^-)$ and γ above expectations in Pb+Pb collisions at 158 – and 40 A GeV for $m(e^+e^-)$ [9] –, is observed above energy density $\epsilon_i \sim 1$ GeV/fm^3. It is not seen in p+A reactions at 158 GeV/N, which correspond to $\epsilon_i < 1$ GeV/fm^3.
The energy density dependence of strangeness production, investigated for the first time in [20]

[a] However the enhancement seen in the ϕ/π ratio in p+A over p+p collisions at 158 GeV per nucleon by NA49 [19] is restricted in the forward rapidity region, while this ratio has not yet been compared at midrapidity and at full acceptance.

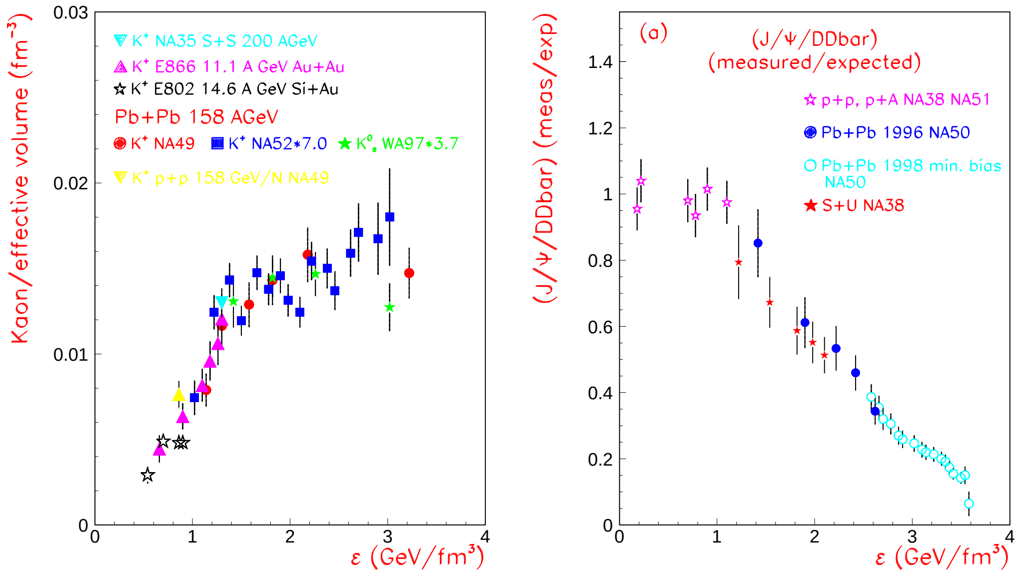

Figure 1: Left: The kaon ($\sim K^+$) multiplicity over the effective volume of the particle source, is shown as a function of the initial energy density (ϵ) [20]. Right: The $J/\Psi/D\overline{D}$ (measured/'expected') ratio is shown as a function of the initial energy density (ϵ) achieved in the collisions investigated [20].

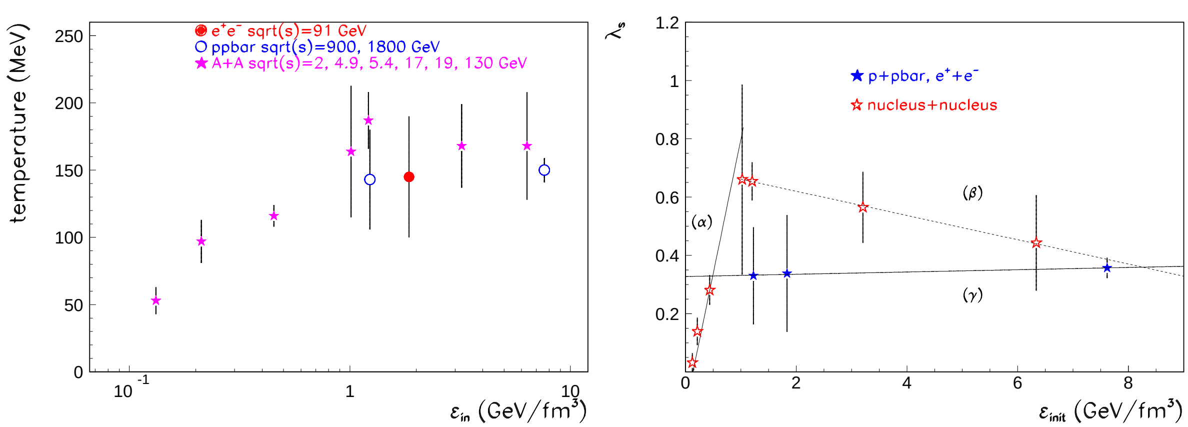

Figure 2: Left: The temperature extrapolated to zero μ_B along an isentropic path, as a function of the initial energy density for several A+A, hadron+hadron and e^+e^- collisions. Right: The λ_s factor as a function of the initial energy density for several A+A, hadron+hadron and e^+e^- collisions. The lines (α), (β) correspond to nonzero μ_B states, while the line γ to μ_B=0 states. We demand for the fits confidence level $> 10\%$ [22].

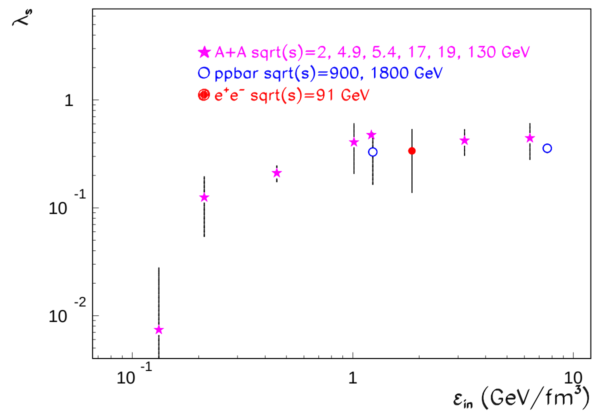

Figure 3: The λ_s factor extrapolated to zero fugacities along an isentropic path, as a function of the initial energy density for several nucleus+nucleus, hadron+hadron and lepton+lepton collisions. We demand for the fits confidence level > 10% [22].

reveals a dramatic change of the kaon number density near $\epsilon_i = 1.3$ GeV/fm^3 (figure 1 left). This ϵ_i coincides with the ϵ_i at which the suppression of the Ψ'/DY ratio sets in [23], while the suppression of the $J/\Psi/DY$ ratio starts at a higher ϵ_i of 2.2 GeV/fm^3 [4].

It is well possible, that the critical energy density revealed by strangeness (figure 1 left) –and which possibly shows up also in the Ψ'/DY suppression– is ~ 1 GeV/fm^3, and the dissociation of J/Ψ occurs at an overcritical $\epsilon_{J/\Psi,dissoc} > \epsilon_{crit}$. However, it is also possible, that all $c\overline{c}$ states dissociate almost simoultaneously at ϵ_{crit}. This follows, assuming that the open charm production is enhanced in S+U and Pb+Pb collisions at 200 and 158 A GeV, following the analysis of NA50 [7]. In this case the relevant quantity to search for the J/Ψ suppresion becomes the $J/\Psi/D\overline{D}$ ratio. As shown in figure 1 right, this ratio is suppressed above $\epsilon_i = 1$ GeV/fm^3, and therefore at the same ϵ_i at which strangeness enhancement sets in (figure 1 left).

We remark that the two behaviour (of $J/\Psi/DY$ and $J/\Psi/D\overline{D}$) are not compatible. It appears therefore that a direct measurement [24] of open charm is crucial for the interpretation of the J/Ψ suppression pattern.

Another missing piece of information concerning J/Ψ, is data from $p\overline{p}$ or pp collisions at ϵ_i between 1 and 3 GeV/fm^3, that is, from Tevatron and RHIC.

3 Is there evidence for the QCD phase transition in global observables ? Can we extract the critical energy density of QCD from the data ? – Questions (b) and (c)

It is a fact, resulting from noumerous thermodynamic analyses [25], that the various $p + p$ and $A + A$ reactions studied searching for the QCD phase transition, are described by different baryochemical potentials. We discuss in the following, what this implies.

We follow a Gedankenexperiment, in which we identify the water-steam phase transition: We fill a box with water and look for the water-vapour phase transition without tools to detect vapour. Each time the transition to vapour (=QGP) occurs we thus wait until the vapour condensates back to water (=hadron gas), in order to measure its temperature. We make a plot of the water temperature as a function of the applied heat, which rises and saturates at the value of $\sim 100^o$ Celsius. Adding salt to water and repeating the experiment would result in different critical

values rising with salinity.
The baryochemical potential is like salt for hadronic systems. To achieve measuring one single curve one has to use the same salinity. Therefore, we arrive at the conclusion, that when extrapolating all measured $A+A$ and $p+p$ systems to the same μ_B value (the simplest one being zero), the border of the QCD phase transition can be drawn and the critical energy density can be extracted selfconsistently from the data, independent of a model which predicts where the boundary must be [21].

We perform this extrapolation in a global analysis of e^+e^-, $p+p$, $p+\overline{p}$ and $A+A$ collisions at $\sqrt{s}$ from 2.6 to 1800 GeV per N+N pair [2,22]. The extrapolation is performed along paths of equal 1) density 2) energy density and 3) entropy density. All three methods give similar results. The resulting T at chemical freeze out and at zero μ_B indeed rises and saturates for all systems which reach $\epsilon_i \geq 1$ GeV/fm^3, as shown in figure 2 left.
We interpret this behaviour as universally mapping out the QCD phase transition in particle and nuclear reactions [21,2,22,26]. The critical energy density can therefore be extracted from the data: $\epsilon_{crit} = 1 \pm 0.3$ GeV/fm^3.
We therefore arrive at a new interpretation of the QCD phase transition:
1) the discriminating parameter is the initially reached energy density
2) all reactions, which agree with a thermodynamic description and reach $\epsilon_i > \epsilon_{crit}$, went through the phase transition and back.
3) No 'critical volume' appears to be needed, which would exclude e.g. $p\overline{p}$ collisions from going through the phase transition, once ϵ_{crit} is reached.
However, as far as the 'critical volume' is concerned, the opposite conclusion has been reached in the literature based on the increase of strangeness in $A+A$ as compared to $p+p$ collisions at the same $\sqrt{s}$ [27]. Why this is not so, is the subject of the following section.

4 A reinterpretation of strangeness as QGP signature – Questions (d) and (e)

What is the energy density dependence of a global measure of strangeness, rather than only the kaon number density (seen in figure 1 left) ? We show in figure 2 right, that the 'strangeness suppression factor' λ_s in A+A collisions (all open points), increases until $\epsilon_i = 1$ GeV/fm^3, and then drops. The λ_s in $p+\overline{p}$ collisions (all closed points), defines the μ_B=0 line in this plot.
It appears from this figure that there is no sudden drop towards the higher ϵ_i and saturation of λ_s in A+A collisions right after $\sqrt{s}$=40 GeV, as discussed in [16], but a continuous decrease, until the $\mu_B = 0$ limit of λ_s is reached at ϵ_i = 8-9 GeV/fm^3, probably within the reach of the LHC [22]. This fact becomes visible, when plotting λ_s as a function of ϵ_i, instead of $\sqrt{s}$. This is an important change, as e.g. central p+p, S+S and Pb+Pb collisions at the same $\sqrt{s}$, will all reach very different ϵ_i.
As shown in figure 3 λ_s at μ_B=0, exhibits a universal behaviour similar to the temperature, rising until $\epsilon_i \sim 1$ GeV/fm^3 and saturating above, for all reactions. It appears from this figure that strangeness is not significantly enhanced in A+A collisions as compared to $p+\overline{p}$ collisions at the same ϵ_i. That is, no 'critical volume' is needed. [b]

[b] The somewhat lower λ_s values in $p+\overline{p}$ collisions as compared to A+A collisions, reflect the lower temperature of the $p+\overline{p}$ collisions as seen in figure 2. Why is the temperature systematically lower in the $p+\overline{p}$ collisions ? One possible explanation is obtained, when visualizing the paths of the different systems in the T, μ_b plane, while going from the plasma phase towards their hadronic freeze out: All systems with nonzero but relatively small baryochemical potentials during hadronization, isentropic expansion and cooling after the transition, follow a curved path leading them systematically to higher μ_B and higher T, as compared to a straight path down at the same μ_B. On the other side all systems with zero μ_B will hadronize and cool until their freeze-out, following a straight path down, allways at zero μ_B. It therefore appears plausible, that all systems with nonzero μ_B will end up at the chemical freeze out with a higher temperature as compared to the systems with zero μ_B, provided

Strangeness is however enhanced in all systems reaching and exceeding the ϵ_{crit} of ~ 1 GeV/fm^3 as compared to the ones which are below, following the temperature. Within this new interpretation of strangeness as QGP signature, recent puzzles discussed in the introduction, can be naturally explained. In particular
a) the increase of the double ratio K/π(A+A/p+p) with decreasing $\sqrt{s}$ [15],
b) the maximum of K^+/π^+ [17] and of λ_s (figure 2 right) at 40 A GeV Pb+Pb collisions,
c) the difference in the $\sqrt{s}$ behaviour of K^+/π^+ and K^-/π^- [17]
d) the difference between the $\sqrt{s}$ behaviour of K^+/π^+ at midrapidity and in full acceptance [18] and
e) the strangeness enhancement seen partly in p+A data as compared to p+p [19], can be understood as due to the different μ_B of the compared reaction systems, and to the fact that the comparison at the same $\sqrt{s}$ for different particles, is not at the same ϵ_i. In the particular case of the ϕ/π ratio in forward rapidity [19], (point (e)) the rapidity dependence of μ_B is also relevant. As point (d) is concerned, the μ_B at midrapidity is minimal, therefore the K^+/π^+ ratio at y_{cm}, does not show the drop seen in the full acceptance K^+/π^+ versus $\sqrt{s}$.

5 Conclusions

We present a new interpretation of the QCD phase transition and of strangeness as QGP signature. The starting point of this analysis is the extraction of thermodynamic parameters describing the final state of e^+e^-, $p+p$, $p+\overline{p}$ and $A+A$ reactions between $\sqrt{s}=2.6$ and 1800 GeV per N+N pair [21,2,22]. The main new idea is to extrapolate these parameters to zero chemical potentials [21,2,22]. We then study the temperature and the 'strangeness suppression factor' λ_s ($\lambda_s = \frac{2\overline{s}}{\overline{u}+\overline{d}}$) as a function of the energy density reached early in each collision (initial energy density ϵ_i).
We arrive at the following conclusions:
1) After extrapolation to μ_B=0 the temperature rises with ϵ_i, and saturates above $\epsilon_i \sim 1$ GeV/fm^3. We interpret this behaviour as mapping out the QCD phase transition universally in particle and nuclear reactions.
In analogy to a water-steam phase transition, the systems which reach and/or exceed the critical energy density, have to hadronize back to the maximum allowed hadronic temperature and a little below, therefore exhibiting a saturating limiting temperature (in analogy to 100^o C). The extrapolation to μ_B=0, is analogous to extracting the salt out of the water, in order to be able to measure a universal T_c.
2) As both $p+\overline{p}$ and A+A reactions exhibit this behaviour once they exceed ϵ_{crit}, it appears that the energy density is the only discriminating parameter of this transition, and no 'critical volume' is needed in order e.g. to achieve thermalization. [c]
3) Strangeness is not significantly increased in nucleus nucleus collisions as compared to elementary particle collisions, if it is compared 1) at the same (zero) chemical potential and 2) at the same initial energy density. However, λ_s is found to significantly increase in all systems which reach or exceed $\epsilon_i \sim 1$ GeV$/fm^3$, as compared to all systems which do not. Strangeness is found to follow closely the temperature, rising until $\epsilon_i \sim 1$ GeV$/fm^3$ and saturating along the border of the QCD phase transition, namely above 1 GeV$/fm^3$.
4) This allows us to extract in a model independent way the critical energy density of the QCD phase transition from the data in particular $\epsilon_{critical} = 1 \pm 0.3$ GeV$/fm^3$ as well as the limiting T and λ_s values [2].

they do not stop exactly on the transition curve [28].

[c] It is conceivable that external probes as $c\overline{c}$ color screenig and jet quenching, have a different dependence on 'critical volume' and/or on $\sqrt{s}$ than the global observables which are ingredients of the QGP itself, namely thermalised $u, \overline{u}, d, \overline{d}, s, \overline{s}$ quarks and gluons. This possibility will be probed at SPS, RHIC and LHC.

5) The so called 'strangeness suppression', namely the decrease of the K/π ratio (or equivalently of λ_s) with $\sqrt{s}$, from its value in Pb+Pb collisions at 40 A GeV towards 158 A GeV, is explained as reflecting the varying chemical potentials of the heavy ion systems.
6) Several other experimental observations have the same origin:
• the increase of the double ratio K/π (A+A/p+p) with decreasing $\sqrt{s}$.
• the flatter behaviour of the K/π ratio as a function of $\sqrt{s}$ when extracted at midrapidity as opposed to the full acceptance.
• the difference in the $\sqrt{s}$ dependence of K^+/π^+ and K^-/π^- ratios.
• the strangeness enhancement seen partly in p+A data as compared to p+p [19].
The above discussion leads to the expectation that A+A as well as p+p collisions at the LHC are both well above the critical energy density for the QCD phase transition and should be investigated both in this spirit.

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